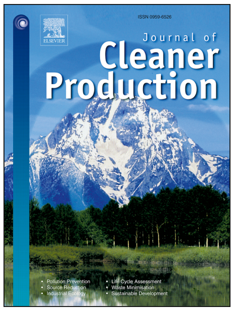

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Life cycle assessment of organic photovoltaic charger use in Europe: the role of product use intensity and irradiation

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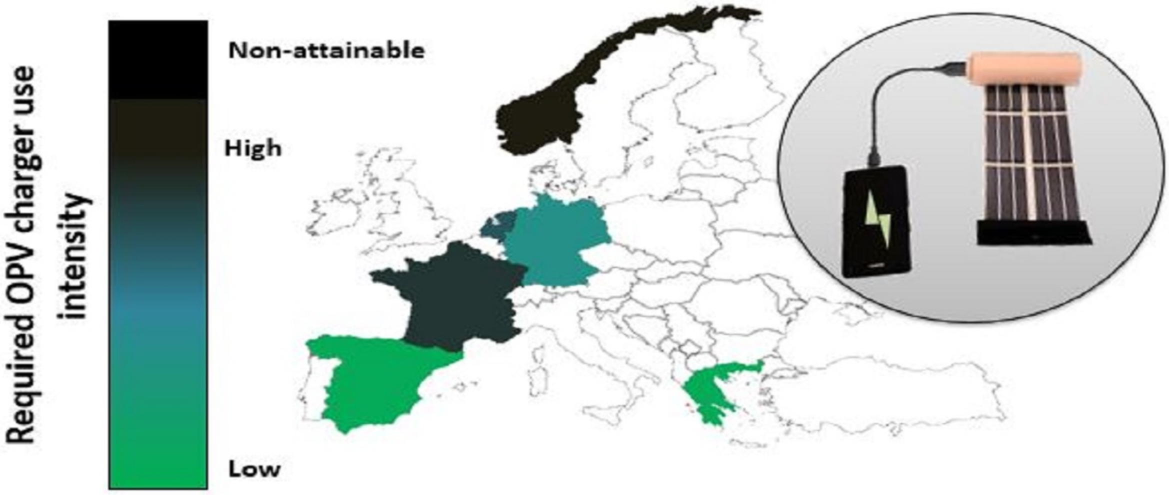

Required OPV charger use intensity
Non-attainable
High
Low

Life cycle assessment of organic photovoltaic charger use in Europe: the role of product use intensity and irradiation

Solar chargers for mobile phones are the first integration of organic photovoltaic (OPV) technology into commercial products. Although environmental impacts of OPVs have been studied extensively, the performance of chargers have been narrowly examined in reference to intensity of their use and use geographies. To explore these aspects, we study the environmental impacts of OPV chargers considering the charger as a substitute for a local electricity grid supply for charging a mobile phone. A consequential life-cycle assessment (LCA) was carried out to evaluate the environmental performance of the OPV charger in six European countries representative of different electricity grids and solar irradiation contexts. Particular effort is made to explore the implications of use intensity of the charger and determine a frequency at which charger is competitive. The results suggest that using an OPV charger has the potential to be environmentally friendly only in countries with high fossil-fuel share in their electricity supplies. The OPV charger is environmentally beneficial in Greece and Spain across most of the evaluated impact categories if used 100-120 times per year, which is practical given the high solar insulation in the two countries. Charging a phone with OPV in Germany or the Netherlands is environmentally-friendly only under conditions of intensive use of the device, or for selective impact categories. In the category of climate change, charging with OPV would represent an improvement in Greece and Germany. In two countries a phone-charging supported by OPV generates 2.5kg of CO_2-equivalents per year in comparison to 2.9-3kg CO_2-equivalents charging from the grid. Phone-charging supported by OPV in Norway and France is more impactful than using the grid for the majority of impact categories, including the category of climate change. The study contributes a novel methodology for looking at photovoltaic technology and helps inform users and policymakers who should consider the local context before an adoption of environmental technologies.

KEYWORDS: solar charger; organic photovoltaics; consequential life cycle assessment; use intensity; solar irradiation; European electricity grid

1. INTRODUCTION

Photovoltaic (PV) technology has been proposed as a more sustainable alternative to contemporary fossil fuel-based energy supply. Even though impacts are created during the manufacturing and disposal of PV products, overall improvements, especially in terms of greenhouse gasses mitigation, are significant [1]. From a range of photovoltaic technologies developed over several decades, the third generation organic PV (OPV) technology is advocated for superior eco-efficiency performance and distinct physical and electrochemical properties that could increase the range of PV products [2], [3]. Compared to conventional silicon solar cells, OPVs have shown to have lower environmental impacts and shorter energy payback times [1], [4]–[9], and when applied in the chargers for mobile phones [10], [11], portable lighting systems [12], and solar panels [1], [11].

In practice, however, photovoltaics more often compete with other energy supply systems, in which case an aspect of the intensity of their use becomes more prominent and sometimes critical to their performance. Environmental impacts associated with the unit of PV electricity are created mostly during the production of PV device, while the use of PV devices when electricity is generated is virtually emission-free. Such disposition of impacts across life cycle phases of PV products prompts impacts to be lower with the more intensive use of PV device. Main factors influencing the use intensity of PV produces, are the choice of PV product integration and the geographical context of their application (i.e., solar irradiation).

The aspect of use intensity on perceived greenness of PV electricity supply presents a challenge to prospective product integration of OPV technology as a portable solar charger for the mobile phones. Even though these chargers integrate potentially greener OPV technology, they are used for only selective appliances such as mobile phones, headphones, cameras or other small electronic devices to facilitate on-demand charging in which instance the use could be expected to occur at a lower and intermittent frequency in comparison to stationary outdoors PV systems. OPV chargers are lightweight and portable and could easily be carried on person as a possible alternative to a powerbank charger and standard outlet supplying electricity from the local grid.

Two studies that explored environmental impacts of using a charger, narrowly explore an aspect of charger use intensity and reach different conclusions. A study by Tsang et al. (2016) explored impacts of the charger in comparison to amorphous silicon as a substitute in which OPV was compared more favorably [11]. Benatto at al. (2017) investigated the OPV charger as a substitute to a local electricity grid and amorphous silicon charger and has shown that OPV charger is not preferred to charge a phone in China and Denmark [10]. The results apply to the limited geographical scope and are based on a single use-intensity, largely neglecting intermittent use-profile of the charger, which is of particular concern to the results of the latter study where OPV is compared with electricity grid as a very different energy supply system. The competitiveness of OPV charger over amorphous silicon alternative was also ruled differently, which comes likely as a consequence of different assumptions of cell infrastructure, and expectations of efficiencies and lifetimes of the OPV cell.

Not conclusive to the studies on OPV chargers, modeling of intermittently used PV devices that resemble similar use behavior to that of PV chargers such as solar tents and solar backpacks, have not been performed to our knowledge. In the literature, intermittency of PV systems has been more readily discussed as a constraint to reliable energy supply [13], and intermittency of solar irradiation [14], rather than as a consequence of use-profile of PV device.

Taking aforementioned limitations, including the diverging results, geographical coverage and narrow use intensity assumptions of current studies on OPV charger, and also general lack of studies exploring intermittency of PV product use in assessment of environmental impacts, we investigate if the use of OPV charger as a substitute to the conventional electricity supply grid could reduce the impacts of charging a mobile phone. We look more closely at the device use intensity while exploring the broad geographic scope of Europe. The information is presented in the manner to achieve more comprehensive understanding of potential implications of the charger use while offering an original methodology to quantify the influence of solar irradiation for intermittently used PV devices. The methods and findings provided throughout this study could serve as valuable information to technology developers and policymakers who should consider product integration of this technology and the geographical context of its application.

2. MATERIALS AND METHODS

The comparison between OPV charger and grid was carried out using consequential approach in LCA. Both direct and indirect environmental impacts considered through this approach are best suited for more perspective and context relevant assessment of emerging technologies and energy supply systems [15]–[17].

Consistent with recommendations outlined in ISO 14040:2006 and ISO14044:2006 standards, LCA is carried out through, four phases: (1) goal and scope, (2) life cycle inventory, (3) life cycle impact assessment and (4) interpretation [18], [19]. The first two phases are described in the current materials and methods section, and the third and fourth phases constitute the results section of this paper.

2.1.Goal and scope

2.1.1. Goal definition

The goal of this study was to investigate the environmental consequences of using an OPV solar charger as a substitute for the electricity grid to charge a mobile phone in Europe, while specifically investigating the aspect of charger use-intensity and influence of irradiation on anticipated intermittent use. The study findings are expected to support OPV technology development and product integration.

2.1.2. Functional unit

The functional unit (FU) for comparison between the OPV charger and the grid, is to charge a phone battery of 2000 mAh every day for five years. The selected capacity of 2000 mAh can be viewed either as charging a smaller battery or only partially charging a battery of bigger capacity. We consider this as a meaningful usage capacity considering the current designs of smartphones. As a reference, the iPhone 8 has a battery capacity of 1821 mAh, and the Samsung Galaxy S8 3000 mAh. To charge a 2000 mAh battery using a standard 5V USB port, 10 Wh of electricity is drawn and stored in the mobile phone battery.

2.1.3. System boundaries

The environmental analysis of the OPV charger device considers impacts arising from all life cycle stages including raw material extraction, manufacturing, use, and disposal. Assumptions of charger design and operating performances are adopted from previous works [6], [11]. Included is a stand-alone 10 Wp (Watt-peak) solar charger (without battery power bank), with 0.2 m^2 of OPV panel and plastic casing. Additionally, this study includes a USB port which was not considered in a previous works due to a lack of data [11]. Consistent with Tsang et al. (2016), the structure of the OPV cell consists of two electrodes, an electron hole transport layer, an active layer, and a substrate. The active layer consists of fullerene derivative phenyl-C61-butyric acid methyl ester (PCBM) as a donor, and co-polymer polythiophene polymer poly(3-hexylthiophene) (P3HT) as an acceptor material, embedded in the form of bulk-heterojunction. Charge separation is facilitated using a transparent positive electrode of indium tin oxide, and the hole transport layer from molybdenum trioxide. A back electrode is from aluminum covered by the thin layer of lithium fluoride. A laminate is assumed from polyethylene terephthalate (PET). The OPV cell operates at 5% efficiency and five years lifetime, taken as a compromise between practical and laboratory performances [6]. Disposal of the charger was modeled assuming incineration, an established waste disposal route and dominant waste treatment method for municipal solid waste in several countries in northern and western Europe [20]. Incineration is only marginally better than landfilling a solar charger, another likely waste disposal alternative for the charger [11]. The charger is assumed to be used only for charging a mobile phone, and not the other electronic devices such as cameras or headphones.

2.1.4. Impact assessment and interpretation methodology

The relative comparison between the OPV charger and the grid was carried out including (1) direct comparison and (2) break-even comparison. Moreover, the results from the two comparisons are interpreted in view of solar irradiation constraints. Comparison and interpretation approaches are represented by framework in Figure 1.

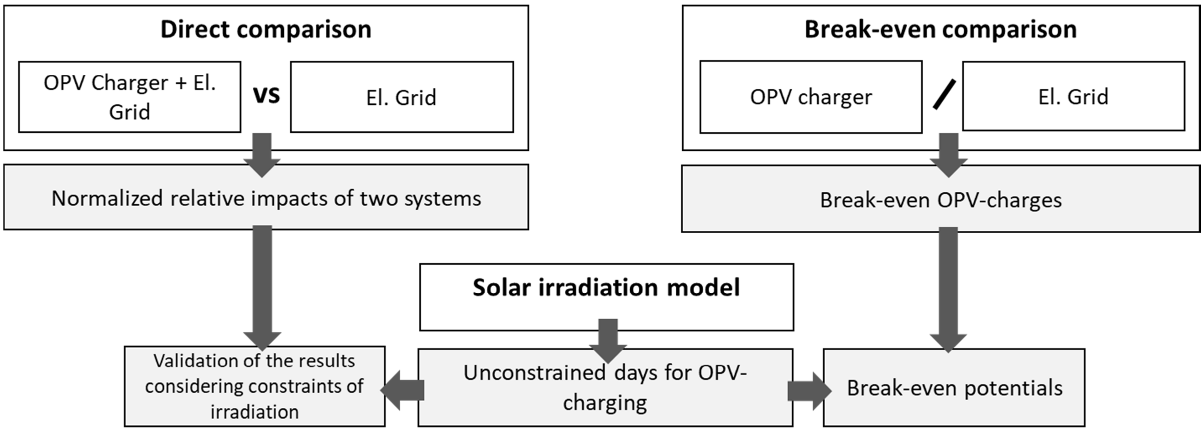


Figure 1. A framework describing comparative steps in this study and the irradiation model used for interpretation.

The direct comparison represents the conventional approach in LCA to calculate impacts between competing product systems using normalized values in the range 0-100. In this case, two product systems for charging a mobile phone are compared: (1) combining a solar charger and electricity grid, and (2) charging solely using the electricity grid. Charging with the solar charger is modeled at 150 times per year, the assumed use frequency adopted from the previous study on OPV chargers [10]. Over five years each product system supplies a total of 18.25 kWh of electricity, of which 7.5 kWh is drawn from the charger.

The break-even comparison, specifically developed in this study, describes the relative environmental impacts of the charger in reference to charger use intensity. Break-even comparison is designed to calculate phone charging frequency using an OPV charger, at which phone charging with the OPV charger (OPV-charges) would equal the impacts of charging with the grid (grid-charges). The break-even OPV-charges are calculated for each impact category using the following equation:

$$break\ even\ OPV\text{–}charges = \frac{env.impact\ of\ production\ and\ disposal\ of\ OPV\ charger}{env.impact\ of\ single\ grid\ charge \cdot lifetime\ of\ OPVcharger}$$

The calculation of OPV-charges allows greater insight in the aspect of use intensity of the charger on its environmental performance and avoids making an assumption of charger use frequency as this is made in the direct comparison. Calculation of break-even OPV-charges could be established due to a different distribution of the environmental impacts across life cycle stages of the charger and grids. In the life cycle of the solar charger, all environmental impacts arise in the production and disposal phase, whereas most of the impacts of grid electricity are generated in the use phase (i.e., when fossil fuels are burned). A frequency of the charger use that exceeds break-even value would render the charger as more eco-efficient.

Interpretation of comparative results from the direct comparison and OPV charges is made through the lens of solar irradiation, given the sunlight as a limiting factor for charger use. We propose a method to incorporate solar irradiation constraints by calculating the number of *unconstrained days* per year which receive sufficient irradiation to fully charge a phone using a solar charger. N*ominal daily irradiation,* above which the day is unconstrained, represents solar irradiation sufficient to charge a 2000 mAh mobile phone battery using 10Wp OPV charger taking practical conditions such as technically required irradiation to charge a battery of given size, and also a portion of energy that wouldn't be utilized in practice. The extent of such unexploited energy would vary depending of irradiation strength and consistency, time of the day, and other practical factors that would obstruct the user from using a charger even when irradiation is available. Ideally, the value of nominal daily irradiation would also benefit from studies on user behavior to better understand how these practical constraints affect charging consistency, but in their absence in scientific literature, that value is assumed. The nominal daily irradiation is proposed as 2.5 kWh/m^2 of irradiation per day which equals to 3-4h of direct sunlight depending on the country and season and is 2.5 times greater than the theoretical irradiation needed to charge a phone battery[1].

Using unconstrained days, it was possible to determine: (1) if OPV-charges set in direct comparison are appropriate, which is the case if an assumed value is lower than the number of unconstrained days for given country, and (2) the *break-even potentials* to express the likelihood of reaching break-even OPV-charges. Break-even potentials are calculated using the following equation:

$$break\text{–}even\ potential = \frac{unconstrained\ days - break\text{–}even\ OPV\text{–}charges}{unconstrained\ days}$$

---

[1] The value of 1kWh/m^2 is derived by considering technical aspects of the charger and amount of energy needed to charge 2000mAh battery. Needed 10Wh of electricity is generated using 10Wp (peak) solar charger with panel area of 0.2m^2 operating at 5% efficiency: 10Wh/(1kWh/m^2·0.05·0.2m^2) =1kWh/m^2.

According to the equation, the break-even potential has a value of zero if a number of unconstrained days are equal or lower than OPV-charges. The potential has a value of one if the number of unconstrained days is twice the number of break-even OPV-charges or greater.

Daily solar irradiation values, used to calculate unconstrained days, were extrapolated from monthly values of Global Horizontal Irradiance derived from the IRENA Global Atlas geographical coordinate grids and several measurement points for each of the six investigated countries (see Supporting Information (SI), Table S2). This irradiation value is expressed in Wh/m^2 and represents the total amount of solar irradiation received on the surface including both direct normal and diffuse horizontal irradiance. The daily irradiation values were extrapolated assuming a linear increase or decrease of irradiation throughout the month.

Emissions arising in the life cycles of the OPV charger and electricity grids were characterized using the ReCiPe 2008 Midpoint (H) (v1.11) impact assessment method, Table 1. The use of the method is in line with previous studies on OPV [6], [11], and an identified need for a broader set of indicators in the modeling of PV and OPV systems [6], [14]. The comprehensive selection of impact categories included in the method was also needed to cover diverse range of impact-profiles characteristic for electricity grids in Europe. OpenLCA 1.6.3 open source LCA software was employed.

Table 1. Environmental impact categories of the ReCiPe midpoint method used in the study

Impact categories	Reference units	Abbreviations
Agricultural land occupation	m^2*a	ALOP
Climate Change	kg CO$_2$ eq	GWP
Fossil depletion	kg oil eq	FDP
Freshwater ecotoxicity	kg 1,4-DB eq	FETP
Freshwater eutrophication	kg P eq	FEP
Human toxicity	kg 1,4-DB eq	HTTP
Ionizing radiation	kg U235 eq	IRP
Marine ecotoxicity	kg 1,4-DB eq	METP
Marine eutrophication	kg N eq	MEP
Metal depletion	kg Fe eq	MDP
Natural land transformation	m^2	LTP
Ozone depletion	kg CFC-11 eq	ODP
Particulate matter formation	kg PM10 eq	PMFP
Photochemical oxidant formation	kg NMVOC	POFP

Terrestrial acidification	kg SO_2 eq	TAP
Terrestrial ecotoxicity	kg 1,4-DB eq	TETP
Urban land occupation	m^2*a	ULOP
Water depletion	m^3	WDP

2.2.Life cycle inventory

Data on materials used in the manufacture of a 10 Wp OPV charger are taken from Tsang et al. (2015), and the inventory pertaining to incineration of the charger from Tsang et al (2016). All the assumptions for compilation of life cycle inventory is thoroughly described in the two studies, and are not repeated here. Only final values are disclosed in the supplement of this paper (Table S3) and materials used shortly described below. Data from the inventory, previously linked to the Ecoinvent v2.2 background data was linked to background data sourced from the Ecoinvent v3.3 consequential database for the average European context [22].

Inventory of OPV charger assume production of PCBM via the pyrolysis technique using toluene as a feedstock. Deposition of all the layers in the OPV cell is assumed to be gravure printed, except for the transparent electrode that assumed the sputtering technique. Chlorobenzene is used as a solvent for the active layer application. Electricity is used for the annealing and printing of panel components and the lamination of the panel. The solar charger uses no produced energy or materials to operate and produces no direct emissions.

A dataset for a single USB port was obtained from Ecoinvent v3.3 as “market for electric connector, peripheral type buss -GLO”.

Data for the country-specific electricity grid mixes are from the Ecoinvent v3.3 consequential database for 2015 as “market for electricity, low voltage” [22], [23].

2.3.Selection of representative countries

Charging scenarios were purposefully chosen to reflect on most diverse sources of electricity present in Europe with intention that broader conclusions can be made in regard to other regions in Europe and beyond. Two criteria were considered significant to the environmental performance of solar chargers: (a) greenhouse gas (GHG) intensity of the country’s electricity grid, and (b) annual solar irradiation available in the country.

GHG emission values were obtained from the Ecoinvent v3.3 consequential database [22], [23], and the yearly solar irradiation values were taken from the International Renewable Energy Agency's Global Atlas [21] (see SI, Table S1, and Table S2).

Finally, out of 17 European countries for which both sets of data were available, six were selected (Figure 2) to represent each of the six partitions in the matrix of electricity supply grids and yearly solar irradiation. The electricity supply grid energy make-up of these countries is quite variable with different single energy source having a high share in country's grid supply: Greece – 11% of oil, Spain – 26% of renewables, Germany – 44% of coal, the Netherlands – 42% of natural gas, France – 78% of nuclear and Norway – 96% of hydro. The GHG - irradiation performances of all 17 countries considered initially is disclosed in SI, Figure S1. Source data for Figure 1, Figure S1, and energy source share is derived from Table S1.

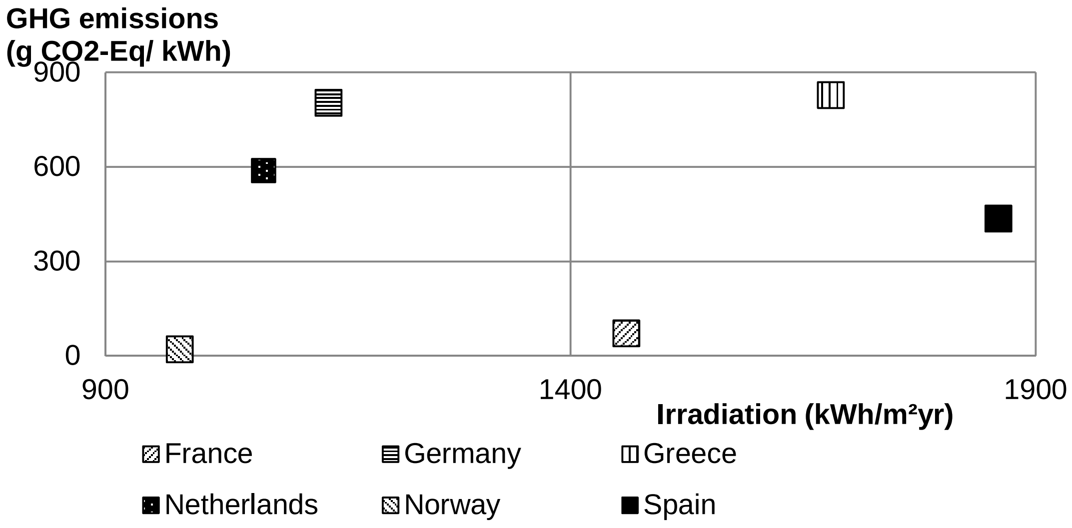


Figure 2. GHG-intensities of electricity supply grids and solar irradiation of six selected countries. Six countries cover a diverse range of possible charger use contexts, hence serve as a representative of Europe.

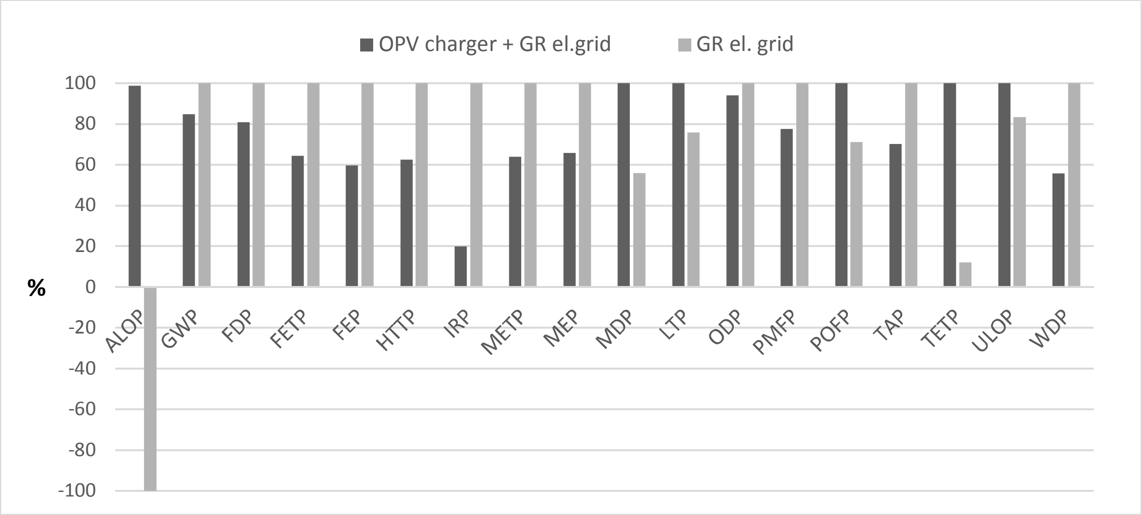
3. RESULTS

The results are presented in two sections. The life cycle impact assessment section, presents the findings from the direct and break-even comparison. In the interpretation section, findings from the direct comparison, and OPV charges determined through break-even comparison, are characterized for their validity and likelihood in view of solar irradiation capacity of investigated countries.

3.1. Life cycle impact assessment

3.1.1. Direct comparison

The relative comparison of a phone charged by combining OPV and grid electricity, versus grid-only charging is shown in Figure 3 (a-f) and absolute values are detailed in SI, Table S4, and Table S5. Results show that the OPV-grid scenario appears competitive across most impact categories in Spain and Greece, and across eight of 18 categories in the Netherlands, ten in Germany, and six in France, while with only three categories showing benefits in Norway.



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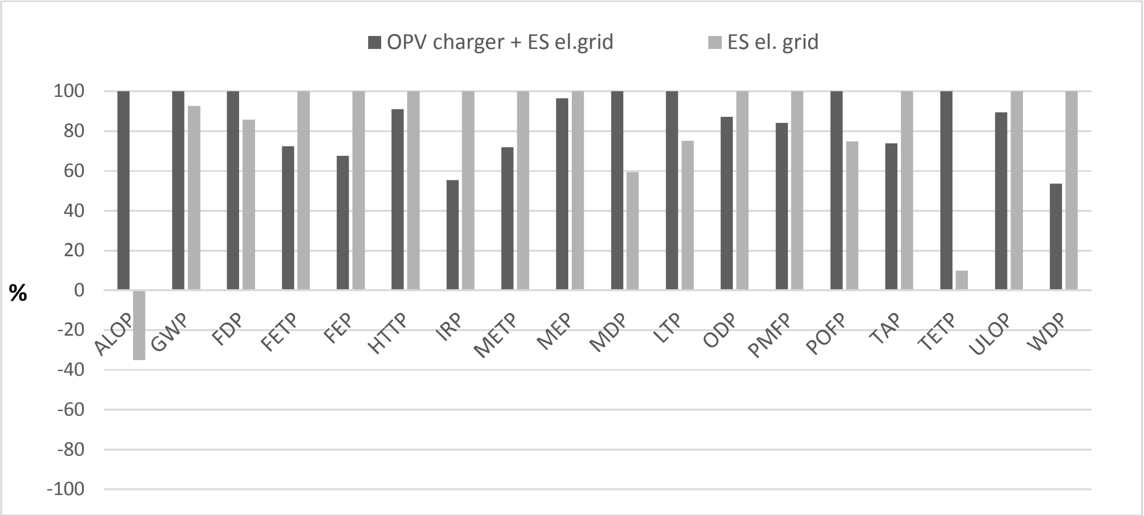
OPV charger + ES el.grid
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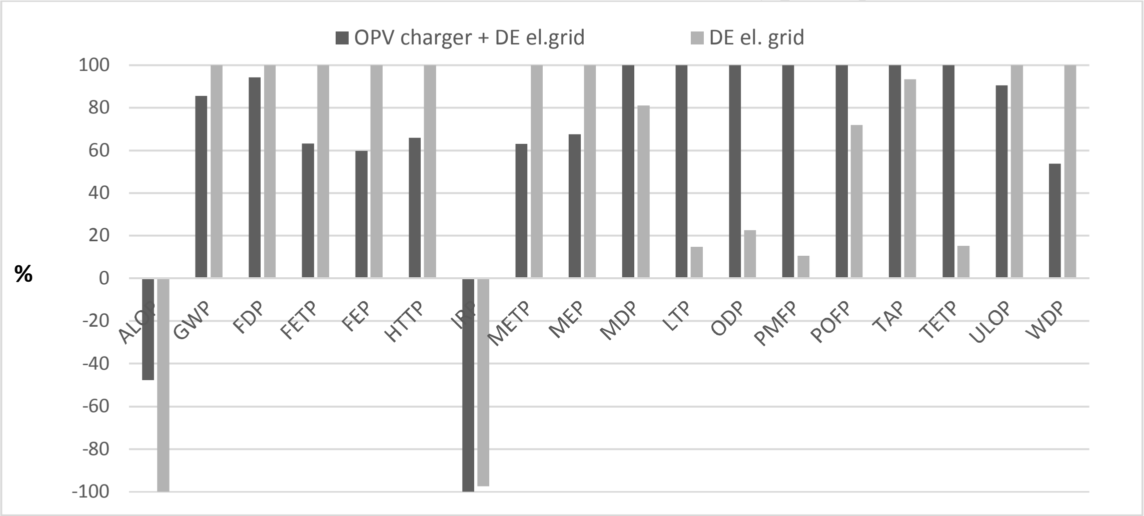
OPV charger + DE el.grid
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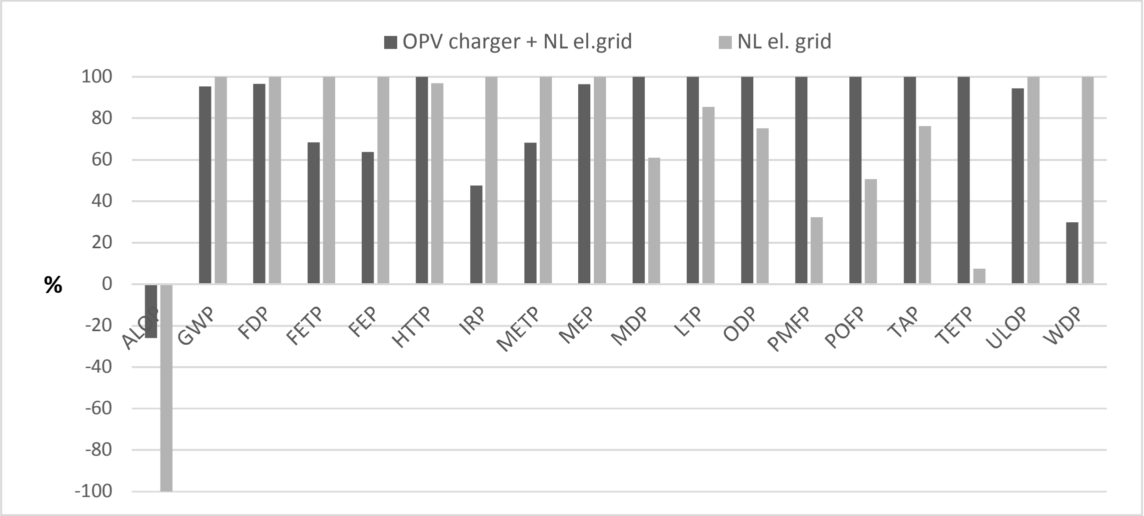
c)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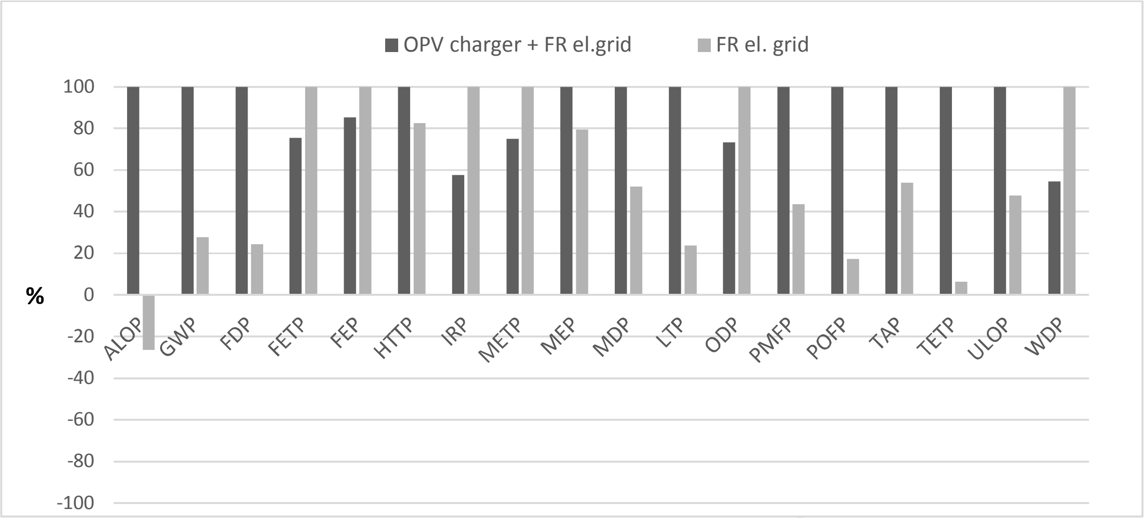
d)

e)



f)

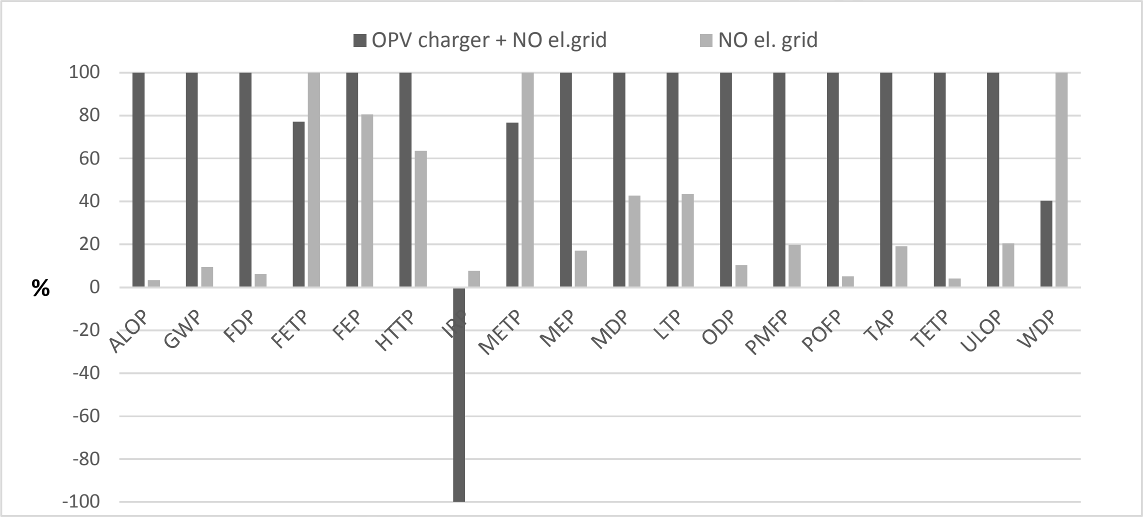


Figure 3 (a-f). Environmental impacts of charging of a 2000mAh phone battery every day for 5 years measured across 18 indicators in six countries: a) Greece, b) Spain, c) Germany, d) the Netherlands, e) France, and f) Norway. Dark-colored bars show the results of combined OPV and grid-charging and lighter bars represent the grid-only system.

Use of OPV chargers is less beneficial in all countries across the potential category impacts of natural land transformation (LTP), ozone depletion (ODP), particulate matter formation (PMFP), and terrestrial ecotoxicity (TETP) due to impacts created as a result of polyester resin production for the charger casing. On the other hand, use of the charger lowers impacts across most of the water-related categories in all countries. That applies to the freshwater ecotoxicity (FETP), marine ecotoxicity (METP) and water depletion potential (WDP) for all countries, and marine and freshwater eutrophication impacts (MEP and FEP), for all countries except Norway. The environmental benefits in these categories are created from the avoided emissions of electricity due to OPV casing incineration. Potential impacts to categories of depletion of other resources provides mixed results. Metal depletion potential (MDP) is worse for the charger-use scenario in all countries, while fossil depletion (FDP) is similar for both product systems, except in France and Norway where electricity grids have notably lower impacts. A potential impact of low-voltage electricity grids in the category of agricultural land occupation (ALOP), comes with environmental benefits for all the countries due to the heat and power co-generation of biogas. Hence, those benefits are more pronounced in the grid-only scenario. The concentration of photochemical oxidants (POFP) that give rise to a summer smog is more impactful for the charger-grid scenario in almost all countries. For the particulate matter formation (PMFP) category, the charger-use scenario proves better only in Spain and Greece. Higher concentration of particulate matter in the electricity mix of both countries appears to be due to the use of lignite and coal. The OPV scenario is lower for ionizing radiation category (IR) due to energy recovery from the charger incineration. Environmental benefits are also observed in the case of German electricity due to heat and power co-generation and the treatment of tailings in uranium milling. A use of OPV charger benefits the climate change (GWP) category in Germany, Greece and the Netherlands. Climate change (GWP), fossil depletion (FDP) and urban land occupation (ULOP) are similar for both grids and OPV charger and are likely to be sensitive to small deviations of OPV-charges above and below the 150 charges per year assumed for the comparison.

3.1.2. Break-even comparison

Table 2 shows break-even OPV-charges. Below 100 OPV-charges the break-even points are reached in nearly all water-related impact categories in all countries except Norway, and in most of the impact categories for Greece. In Spain, breaks in most of the categories can be reached at around 100 OPV-charges. At around 130 OPV-charges roughly half of the impact categories could be reached for Germany and the Netherlands.

Table 2. OPV-charges to break-even with the environmental impacts of the electricity grids in six countries, across 18 impact categories.

Impact category	GR	ES	DE	NL	FR	NO
Agricultural land occupation	-	-	-	-	-	10527
Climate Change	94	179	97	133	1103	3640
Fossil depletion	80	211	129	137	1288	5592
Freshwater ecotoxicity	20	49	15	35	60	67
Freshwater eutrophication	3	32	3	18	96	238
Human toxicity	14	117	26	162	227	360
Ionizing radiation	0	0	160	0	0	0
Marine ecotoxicity	18	48	15	34	59	65
Marine eutrophication	25	138	32	137	244	1921
Metal depletion	439	400	235	384	487	641
Natural land transformation	266	271	2250	212	1319	627
Ozone depletion	128	103	1395	270	52	3345
Particulate matter formation	68	92	3204	912	622	1635
Photochemical oxidant formation	299	273	293	506	1899	7010
Terrestrial acidification	41	55	176	263	461	1691
Terrestrial ecotoxicity	2810	3453	2160	4756	5548	8910
Urban land occupation	223	111	115	130	550	1569
Water depletion	0	0	0	0	0	0

Break-even charges can only be derived for impact categories for which the more intensive use of solar charger leads to a reduction in the environmental impacts. Consequently, for impact categories where impacts of the grid charging are negative due to indirect environmental benefits, the break-even values could not be implied. This is the case for the category of agricultural land occupation for all countries except Norway. Inversely, for impact categories where impacts of the OPV charging are negative due to environmental benefits, as such is the case for the categories of irradiation potential, and water depletion, impact categories are assigned zero value.

3.2. Interpretation of the results using solar irradiation constraints

3.2.1. Characterization of OPV-charges used for the direct comparison

The unconstrained days were calculated as 305 in Spain, 282 Greece, 242 France, 205 Germany, 197 the Netherlands and 181 Norway. These values appear higher than the baseline assumption of 150 OPV-charges suggesting that the results shown in Figure 3 (a-f) are practical. However, given differences between assumed charges and unconstrained days in countries, results of the comparison for Spain, Greece and France are more conservative and thus more compelling than the conclusions derived for the Netherlands, Germany and Norway.

3.2.2. Characterization of break-even OPV charges: break-even potentials

Break-even potentials are shown in Table 3. The high potentials (above 0.5) of achieving break-even OPV-charges applies to Spain and Greece, with the charger breaking even in majority of the impact categories. In the Netherlands and Germany, even though the break-even OPV charges can be achieved in most of the categories, the potentials of reaching break-even values are small. For example, for the Netherlands, in five of ten categories where OPV break-even charges could be achieved, the potentials are below 0.34. For Norway and France, most of the impact categories are not attainable. However, the break-even potentials in the remaining categories in France are high, suggesting a high likelihood of making improvements in specific categories by using the charger.

Break-even potentials mostly allow to observe relative likelihood among countries to reach break-even OPV-charges and highlight that similar break-even values have different potentials to be reached depending of country’s irradiation. For instance, for Greece and Germany the break-even values of the category of climate change (94 and 97, respectively), although similar, translate in to higher potential for Greece (0.67) than Germany (0.53).

Table 3. Break-even potentials showing the relative likelihood of reaching OPV-charges.

	Break-even OPV-charging potentials					
	GR	**ES**	**DE**	**NL**	**FR**	**NO**
Agricultural land occupation	0.00	0.00	0.00	0.00	0.00	0.00
Climate Change	0.67	0.41	0.53	0.32	0.00	0.00
Fossil depletion	0.72	0.31	0.37	0.30	0.00	0.00
Freshwater ecotoxicity	0.93	0.84	0.93	0.82	0.75	0.63
Freshwater eutrophication	0.99	0.90	0.99	0.91	0.60	0.00
Human toxicity	0.95	0.62	0.87	0.18	0.06	0.00
Ionising radiation	1.00	1.00	0.22	1.00	1.00	1.00
Marine ecotoxicity	0.94	0.84	0.93	0.83	0.76	0.64
Marine eutrophication	0.91	0.55	0.84	0.30	0.00	0.00
Metal depletion	0.00	0.00	0.00	0.00	0.00	0.00
Natural land transformation	0.06	0.11	0.00	0.00	0.00	0.00
Ozone depletion	0.55	0.66	0.00	0.00	0.79	0.00

Particulate matter formation	0.76	0.70	0.00	0.00	0.00	0.00
Photochemical oxidant formation	0.00	0.10	0.00	0.00	0.00	0.00
Terrestrial acidification	0.85	0.82	0.14	0.00	0.00	0.00
Terrestrial ecotoxicity	0.00	0.00	0.00	0.00	0.00	0.00
Urban land occupation	0.21	0.64	0.44	0.34	0.00	0.00
Water depletion	1.00	1.00	1.00	1.00	1.00	1.00

Break-even potentials in range 0.5-1 signify high potentials, and 0-0.5low-to-medium likelihood to reach OPV-charges. Potentials with the values of zero represent categories for which break-even value could not be achieved as break-even charges are greater than unconstrained days.

4. DISCUSSION

Contrary to the previous studies [1], [4]–[9], our research shows that OPV technology is not always environmentally-friendly and that the choice of integrating PV products plays a decisive role. In most of the investigated countries, the intensive use of charger is needed if charging with OPV is to be considered an improvement. Even in countries with dirtier grids, such as Greece where electricity grid supply is dominated by coal, and in Spain where grid supply is mostly based on use of oil, coal, and biomass, the charger needs to be used on average 100 times to have equal impacts with competing grids, and more intensively to be categorized as "green". Overall, the OPV charger is more suited for targeting improvements in selective impact categories, rather than seeking to obtain improvements in all categories. Thus, given priority to specific impact categories, the charger could also be preferred in Germany, the Netherlands, and even France.

An observation to favorable charger performance for category of climate change in countries with dirtier electricity grids, echoes in earlier works where the charger was rated worse in Denmark, which has a high ratio of wind power, and positively in China where there is a high share of fossil fuels in the electricity grid [10]. However, for other impact categories our results vary which likely come about as a result of different assumptions for OPV cell design, lower operating efficiencies assumed, or the different version of Ecoinvent database used for modeling [24]. The type of analysis that considers geographic variables for renewable energy is similar to work being undertaken to compare electric vehicles with cars with internal combustion engine [25]. However, electric vehicles do better on cleaner grids, whereas OPV chargers compare better in the context of polluting grids.

Principally, if CO_2 emission-equivalents are presumed as indicative of fuel share of electricity (refer to Figure 2 and Figure S1), our findings could be extended to assume charger performance in other countries with similar solar irradiation potentials and fuel shares of their grid supplies. In that case, the environmentally advantageous use of OPV charger within the reasonable frequencies of charger use could be achieved in Italy and Portugal. Use in the Czech Republic, the United Kingdom, and Luxemburg will result in environmental trade-offs between similar impact categories, whereas, the use of charger in Switzerland, Slovakia, Austria and Belgium would not be accommodating to low-impact phone charging using OPV.

The type of analysis we presented in our study is the first attempt to model the aspect of intermittency of PV devices as a feature of the product use-profile, the aspect which is highly uncertain and a more expected feature of emerging technologies, since a credible estimate of user behavior is more difficult. While the most conventional way to tackle this issue is to assess multiple assumption of charger use involving multiple scenarios and functional proxies, we offer an approach where the estimate of product use can be avoided altogether. Additionally, the demonstrated break-even comparison allows incorporating solar irradiation in the modeling of chargers. Lastly, this novel distance-to-target representation of the results generates information more palatable to the user, hence appealing to circular economy perspective where product user can take more proactive role. Similar approach to modeling could be applied to any consumer product whose performance changes with intensified use.

A main limitation of our work is associated with the assumption of nominal daily irradiation used to derive unconstrained days, that could not be well supported in the current literature on consumer behavior. Although, this is not detrimental to our overall findings as the preference across investigated impact categories is mostly divided between grids and an OPV charger, hence, small to medium variations in solar irradiation are expected to have minor influence on the results. Also, it is important to note that a technical durability of the charger (i.e., five years), although realistic assumption of technology [26], [27], is not necessarily an indication of the actual longevity of use [28]. Both nominal daily irradiation value and expected lifetime assumptions could benefit from behavioral science and agent-based modeling that is increasingly used in environmental studies to estimate consumer behavior [29], [30]. Another viable approach to realize potential for OPV-charging is with the help of ambient light sensors in mobile phones that can inform on user exposure to solar irradiation [31].

Finally, when considering the prospective advantages between OPV chargers and the electricity grid, it is worth noting the differences between the two supply systems in terms of practical considerations like reliability and scale of energy provision. Solar chargers provide the convenience of outdoor charging, and in areas where charging is otherwise not accessible such as developing countries where grid infrastructure is not available. This flexibility and the potential of environmental performance in given countries would make portable OPV systems competitive replacements for diesel generators. On the other hand, grid electricity is often a more reliable electricity source that cannot be entirely replaced by a solar charger. The cost of electricity pertaining to both systems and the social aspects connected to resource use would need to complement this environmental analysis to fully support policy or consumer decision.

5. CONCLUSIONS

The study was carried out to determine if the use of OPV charger provides an improvement over conventional charging of the mobile phone in several countries in Europe while considering the frequency at which the charger is used. Comparison with conventional grid-charging is carried out both for an estimated use-rate of the charger, and inversely by calculating the use rate at eco-efficiency break-even points. Subsequently, the results from both comparative approaches are interpreted accounting for capacity of solar irradiation.

The findings suggest that OPV charger has the potential to be environmentally-friendly in the countries with dirtier electricity supplies and for targeting improvements in select impact categories. Overall, the use of OPV chargers could reduce impacts in water-related categories and increase impacts in categories representing atmospheric pollution. The OPV charger is beneficial in Spain and Greece but cannot compete with low-impact hydro and nuclear power of the grids in Norway and France.

The approach presented in this study constitutes a guiding framework for assessment of intermittently used products and offers a quantitative method for incorporating solar irradiation in modeling of PV products.

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- An OPV charger is compared with electricity grid for charging a mobile phone
- Charger impacts are considered in view ofits use intensity and solar irradiation
- The charger has potential to be eco-friendly in four of six investigated countries
- Improvements in water-related categories are traded for higher impacts to the air